Telerobotics for Human Exploration
Enhancing crew capabilities in deep space

Dr. Terry Fong
Intelligent Robotics Group
NASA Ames Research Center
terry.fong@nasa.gov

irg.arc.nasa.gov
Exploration destinations
(one-way travel times)

- International Space Station (2 days)
- Moon (3-7 days)
- Mars (6-9 months)
- Lagrange Points and other stable lunar orbits (8-10 days)
- Near-Earth Asteroid (3-12 months)

Future missions will be longer, more complex, & require new technology

Robotics and Mobility
Deep Space Habitation
Advanced Spacesuits
Advanced Space Comm
Advanced Propulsion
Resource Utilization
Human-Robot Systems
Telerobotics for Human Exploration

Part 1: Crew Surface Telerobotics
- Crew remotely operates surface robot from spacecraft
- Extends crew capability
- Enables new types of missions

Part 2: Interoperability
- Facilitate systems integration and testing
- Reduce development cost
- Expand international collaboration

Part 3: Common User Interfaces
- Common control modes
- Common interaction paradigms
- Enhance operator efficiency and reduce training time
Surface Telerobotics

Concept of Operations
- Crew remotely operates surface robot from spacecraft
- Proposed by numerous study teams for future missions
- Very little experimental data and validation to date

Candidate Missions
- **L2 Lunar Farside.** Orion MPCV at Earth-Moon L2 and rover on lunar farside surface
- **Near-Earth Asteroid.** NEA dynamics and distance prevent Earth-based manual control
- **Mars Orbit.** Crew operates surface robot when situation precludes Earth control

Credit: NASA GSFC
Studies

Surface Telerobotics
(2012-14, NASA)

Avatar Explore
(2009, CSA)

METERON
(2014 ?, ESA)
Comparison

Avatar Explore (CSA, 2009)
- No Live Interaction
- High Latency (> 1h)
- Low Bandwidth
- Simple Task
  Target Location

Natural Terrain
- Command-Based Control
- Intermittent Comms

Surface Telerobotics (NASA, 2012-14)
- Interactive / Supervisory
- Moderate Latency (< 2s)
- Moderate Bandwidth
- Scouting, Survey
- Inspection, Servicing
- Structured Objects
- Force-Feedback Control
- Continuous Comms

Planetary Rovers Controlled from Orbit
- Real-time Teleoperation
- Low Latency (< 50ms)
- High Bandwidth
- High Degree of Freedom Manipulation

METERON (ESA, 2014 ?)
- Simple Task
  Target Location
- Natural Terrain
- Command-Based Control
- Intermittent Comms

Continuous Comms
NASA Surface Telerobotics

Goals

• Demo **crew-centric control** of surface telerobot from ISS (first operational system)
• Test **human-robot “opscon”** for future deep-space exploration mission
• Obtain **baseline engineering data** of system operation

Approach

• Leverage best practices and findings from **prior ground simulations**
• Collect data from robot software, crew user interfaces, and ops protocols
• Validate & **correlate to prior ground sim** (analog missions 2007-2011)

Implementation

• **Waypoint mission simulation**
• **K10 planetary rover** in ARC Roverscape (outdoor test site)
• **Astronaut on ISS** (10 hr total crew time, ISS Incr. 36)

Key Points

• **Complete human-robot mission sim**: site selection, ground survey, telescope deployment, inspection
• **Telescope proxy**: COTS 75 micron polyimide film roll (no antenna traces, no electronics, no receiver)
• **3.5 hr per crew session** (“just in time” training, system checkout, telerobot ops, & crew debrief)
• **Two control modes**: basic teleop and pre-planned command sequencing (with continuous monitoring)
• **Limited crew user interface**: no sequence planning, no science ops capability, no robot engineering data
Waypoint Mission

**Earth-Moon L2 Lagrange point**
- 60,000 km beyond lunar farside
- Allows station keeping with little fuel
- Crew remotely operates robot on Moon
- Cheaper than human surface mission
- Does not require human-rated lander

**Lunar telescope installation**
- Use telerobot to setup radio telescope on surface
- Requires surface survey, deployment, and inspection / documentation
- Lunar farside = radio quiet zone for low freq. measurements of cosmic dawn

Credit: Lockheed Martin

Credit: Univ. of Colorado / Boulder
Waypoint Mission Simulation (2013)

Phase 0
Pre-Mission Planning
Ground teams plan out telescope deployment and initial rover traverses.

Phase 1
Surveying / Scouting
Crew gathers information needed to finalize the telescope deployment plan.

Phase 2
Telescope Deployment
Crew monitors the rover as it deploys a single arm of a telescope node.

Phase 3
Telescope Inspection
Crew inspects the deployed telescope node looking for tears and folds.

Crew Session 1
Spring

Crew Session 2
June 17

Crew Session 3
July 10

August 8
K10 Planetary Rover @ NASA Ames

NASA Ames Roverscape
Robot Interface (Task Sequence Mode)
Robot Interface (Teleop Mode)

Motion controls

Camera controls

Rover path

Terrain hazards

Rover camera display
Experimental Protocol

Data Collection

Obtain engineering data through automatic and manual data collection

- **Data Communication**: direction (up/down), message type, total volume, etc.
- **Robot Telemetry**: position, orientation, power, health, instrument state, etc.
- **User Interfaces**: mode changes, data input, access to reference data, etc.
- **Robot Operations**: start, end, duration of planning, monitoring, and analysis
- **Crew Questionnaires**: workload, situation awareness, critical incidents

Metrics

Use performance metrics* to analyze data and assess human-robot ops

- **Human**: Bedford workload & SAGAT (situation awareness)
- **Robot**: MTBI, MTCI for productivity and reliability
- **System**: Productive Time, Team Workload, and task specific measures for effectiveness and efficiency of the Human-Robot system

*Performance metrics used for prior analog field tests: 2009 robotic recon, 2010 lunar surface systems, 2010 robotic follow-up, 2009-2011 Pavillion Lakes research project, etc.*
Part 1: Crew Surface Telerobotics
- Crew remotely operates surface robot from spacecraft
- Extends crew capability
- Enables new types of missions

Part 2: Interoperability
- Facilitate systems integration and testing
- Reduce development cost
- Expand international collaboration

Part 3: Common User Interfaces
- Common control modes
- Common interaction paradigms
- Enhance operator efficiency and reduce training time
Modern robots are highly complex systems

- Many software modules (on-board and off-board)
- Distributed development team
- Standardized framework facilitates interoperability

Benefits of interoperability

- Facilitate integration and testing
- Reduce cost and risk
- Enhance operational flexibility and capabilities

Robots that do not speak the same “language” are a major obstacle to collaboration in space exploration …
CCSDS Telerobotics Standard

MOIMS-TEL

- Mission Operation & Info. Management Area
- Telerobotics Working Group
- Develop interoperability standards applicable to multiple projects and missions

Focus

- Compatibility “layer” that facilitates command and data exchange
- Specification for software data structures
  - Message formats
  - Application Programming Interfaces (API)
  - Functional description of standard services

This is NOT …

- All-encompassing system for robot data comm
- Set of standards governing space robotics
Interoperability Standard Development

Approach

- Adopt best practices and lessons learned from relevant work
- Develop recommendations based on future mission needs
- Consider existing CCSDS standards (where appropriate)

Relevant work

- CCSDS Asynchronous Message Service (AMS)
- CCSDS Application Support Services (APP)
- CCSDS Mission Operations (MO)
- IETF Delay-Tolerant Networking (DTN)
- OMG Common Object Request Broker Architecture (CORBA)
- OMG Data-Distribution Service for Real-Time Systems (DDS)
- NASA Robot Application Programming Interface Delegate (RAPID)
- SAE Joint Architecture for Unmanned Systems (JAUS)
- etc.
Robot Application Programming Interface Delegate (RAPID)

- Provides Message Definitions & API
- Provides Common Services API
- Developed by ARC, JPL, and JSC with assistance from GRC, LaRC, and KSC

Implementation

- Uses Data-Distribution Service
  - International standard (OMG)
  - Publish-subscribe communications
- RTI DDS provides data transport (middleware) layer
- Open-source release (Apache 2)
RAPID Robots

K10 planetary rovers

Smart SPHERES

Centaur 2 robot

Lunar Surface Manipulator System

Space Exploration Vehicle

Tri-ATHLETE

X-Arm-2
RAPID User Interfaces

Telerobotics for Human Exploration
Telerobotics for Human Exploration

Part 1: Crew Surface Telerobotics
- Crew remotely operates surface robot from spacecraft
- Extends crew capability
- Enables new types of missions

Part 2: Interoperability
- Facilitate systems integration and testing
- Reduce development cost
- Expand international collaboration

Part 3: Common User Interfaces
- Common control modes
- Common interaction paradigms
- Enhance operator efficiency and reduce training time
Robot User Interfaces

**Space robots**
- Space robots have very diverse forms (size, shape, movement, etc)
- Many different control modes (manual to safeguarded to supervisory)
- Broad range of tasks (mobility, field work, positioning, etc.)

**User interfaces**
- Robots have custom user interfaces and custom interaction modes
- Users need to relearn control methods for each new robot
- Very difficult to port new control modes from robot to robot

Multiple, complex and/or inconsistent robot user interfaces result in increased training, reduced operational efficiency and higher crew workload
Robot User Interfaces

ISS Robotic Work Station

Surface Telerobotics Workbench

R2 Teleop UI

ATHLETE Footfall Planner
Operator Interface Standards

**Industrial Robots**

- ANSI/RIA R15.06-1999
  - Guidelines for industrial robot manufacture, installation, and safeguarding for personnel safety
- ANSI/RIA R15.02-1-1990
  - Guidelines for the design of operator control pendants for robot systems

**Ergonomics**

- NASA Man-Systems Integration Standards
  - Human-systems integration design considerations & requirements
- MIL-STD-1472F
  - General human engineering criteria for military systems
Common User Interfaces

Standardized Interactions

- Common set of commands that will produce **predictable** and **consistent** robot behaviors
- Common **interaction paradigms** (for different control modes)
- Common **information displays** (standard semantics)

Benefits

- Help users avoid inadvertently sending erroneous commands when switching between different types of robots
- Enhance operator efficiency
- Reduce training time (initial & proficiency maintenance)
Common Ground Vehicle Interfaces

Honda Civic

Pontoon boat

Forklift

Riding lawnmower

School bus
Common User Interfaces

How will crew operate

• Surface robots from orbit?
• Side-by-side with robots?
• Many types of robots for different tasks?

Low-Earth Orbit

Deep Space

Asteroids & Near-Earth Objects

Mars, Phobos, & Deimos

International Space Station

Lunar Orbit, Lunar Surface (Global)

Telerobotics for Human Exploration
Part 1: Crew Surface Telerobotics
- Crew remotely operates surface robot from spacecraft
- Extends crew capability
- Enables new types of missions

Part 2: Interoperability
- Facilitate systems integration and testing
- Reduce development cost
- Expand international collaboration

Part 3: Common User Interfaces
- Common control modes
- Common interaction paradigms
- Enhance operator efficiency and reduce training time